Prompt Gamma-ray and Early Afterglow Emission in the External Shock Model

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ABSTRACT

We describe our attempt to determine if gamma-ray burst (GRB) and afterglow emissions could both arise in external shocks for simple GRBs – bursts consisting of just a few peaks in their lightcurves. We calculate peak flux and peak frequency during the gamma-ray burst for ten well observed bursts using the same set of parameters that are determined from modeling afterglow emissions. We find the gamma-ray emission properties for 970508 (which had a single peak lightcurve) fit nicely with the extrapolation of its afterglow data, and therefore this burst was likely produced in the external shock. One can explain two other bursts in this sample as forward shock synchrotron emission provided that the magnetic field parameter during the burst is close to equipartition, and larger by a factor $\sim 10^2$ than the afterglow value at $\sim$ 1day. The remaining seven bursts cannot be explained in the external shock model even if we allow the energy fraction in electrons and magnetic field and the density of the surrounding medium to take on any physically permitted value; the peak of the spectrum is above the cooling frequency, therefore the peak flux is independent of the latter of these two parameters, and is too small by about an order of magnitude than the observed values. We have also considered inverse-Compton scattering in forward and reverse shock regions and find that it can explain the γ-ray emission for a few bursts, but requires the density to be 1–2 orders of magnitude larger than a typical Wolf-Rayet star wind and much larger than permitted by late afterglow observations.

We have also calculated emission from the reverse shock for these ten bursts and find the flux in the optical band for more than half of these bursts to be between 9th and 12th magnitude at the deceleration time if the reverse shock microphysics parameters are same as those found from afterglow modeling and the deceleration time is of order the burst duration. However, the cooling frequency in the reverse shock for most of these bursts is below the optical band, and therefore the observed flux decays rapidly with time (as $\sim t^{-3}$) and is unobservable after a few deceleration times. It is also possible that the deceleration time is much larger than burst duration in which case we expect weak reverse shock emission.

Key words: gamma-rays: bursts, theory, methods: analytical – radiation mechanisms: non-thermal - shock waves

1 INTRODUCTION

The localization of Gamma-Ray Bursts (GRBs) and the discovery of their X-ray afterglows by the *BeppoSAX* satellite in 1997 has greatly improved our understanding of GRBs over the last 7 years. These x-ray, optical, and radio afterglows are thought to be produced when an external shock heats the surrounding medium, with radiation being produced via synchrotron from the heated material. We now also know from the spectroscopic confirmation of the GRB 030329/SN2003dh connection (Matheson et al. 2003, Stanek et al. 2003) that at least some long duration GRBs are pro-

duced by the collapse of massive stars. There is, however, considerable uncertainty surrounding the nature of the inner engine of GRBs, and we lack a definitive understanding for how the γ-ray emission is produced. This paper is an attempt to understand how γ-ray emission is produced in GRBs.

Multiwavelength afterglow data have enabled us to do broadband modeling of late-time afterglows. This broadband modeling results in the determination of burst energy, microphysical shock parameters, beaming angle, and environmental properties (surrounding density and stratification). Further improvements to our understanding of GRBs

requires analysis/modeling of both the GRB and afterglow together, which we undertake here.

In this paper, we use parameters we determine for 10 bursts by modeling their broadband afterglow emissions to extrapolate the radiation calculation back to the burst duration, with the goal of determining whether synchrotron emission from the forward shock can account for both the GRB prompt emission and the late-time afterglow. This is especially applicable for the ∼10% of bursts with a single pulse FRED (fast rise, exponential decline) GRB lightcurve, where a single external shock is expected to produce the emission. This exercise is, however, carried out for all bursts in our sample, including those with moderately complex GRB lightcurves.

Internal shocks were suggested as a mechanism for producing γ-ray emission because external shocks are not capable of producing rapid variability seen in many GRB lightcurves, whereas variability arises naturally in internal shock models, reflecting fluctuations associated with the central engine (Rees & Mészáros 1994; Piran, Shemi & Narayan 1993; Katz 1994). For GRB lightcurves consisting of a single peak or just a few peaks, this rationale for internal shocks does not apply and such bursts could be produced in external shocks.

The determination of kinetic energy release in relativistic ejecta for ten bursts by modeling their broadband afterglow lightcurves suggests that the efficiency for γ-ray production is typically in excess of 50% (Panaitescu & Kumar, 2002 hereafter PK02). Such a high efficiency cannot be achieved in internal shocks; some published claims to the contrary (e.g. Beloborodov, 2000) achieved high efficiency by colliding shells with very large relative Lorentz factor (hereafter LF), however in this case the emergent spectrum peaks at energies much larger than observed values. External shocks, on the other hand, can very efficiently convert bulk kinetic energy to radiation.

In addition to the problem of efficiency for the internal shock model we describe below other reasons for considering the external shock model for the generation of γ-ray emission for many of the ten bursts we consider in this paper (table 1 lists the ten bursts).

The 320-1090 kev light-curve for 990123 consisted of two broad peaks of duration ∼ 10s each. Comparing this time scale with the deceleration time (t_d) of ≲50s – which is inferred from the peak of the prompt optical emission – suggests that γ-ray emission is produced within a factor 2 of the deceleration radius[1]. In the internal shock model for γ-ray production, the near equality of the radius where shells collide to produce γ-rays and the deceleration radius is a coincidence, whereas in the external shock model this is what one expects. It should be noted that the short time scale variability seen in 990123 (Fenimore et al. 1999) had an amplitude of ∼20% and could have arisen due to small scale turbulence in the shocked fluid. The observed low energy spectral index α for this burst was 0.4 ($f_\nu \propto \nu^{0.4}$)

whereas in internal shock models we expect $\alpha \sim -0.5$ due to short cooling time for electrons or low cooling frequency (Ghisellini et al. 1999).

The lightcurve for GRB 970508 was a FRED, 980519 was similar to a FRED, and 000301c lightcurve was perhaps a FRED (Smith et al. 2002), however because of the low temporal resolution of the Ulysses observation (0.5 sec) we are unsure of it. One might expect these bursts to arise in an external shock. Two other bursts in our sample of ten – 980703 & 991208 – had lightcurves consisting of two smooth peaks, and therefore are good candidates for a possible origin in an external shock. GRBs 990510 & 991216 lightcurves had more fluctuations than the bursts mentioned above, however they each had two broad peaks and a number of sub-pulses superimposed on them, and do not require internal shock to produce this modest variability. There are no lightcurves available for the remaining two bursts in our sample, 000418 & 000926, which were both detected by the IPN. It turns out that for all of these bursts, except 970508, the simplest theoretical model of synchrotron emission in the forward shock fails badly to explain their γ-ray emission (§2). Moreover, none of the possibilities we explore in the general framework of an external shock model seem to work satisfactorily.

In two GRBs (990123 and 021211), a bright, steeply falling off ($\sim t^{-2}$) early optical emission was observed. This has been explained by radiation from the reverse shock heated ejecta from the explosion. We have seen this emission from only these two bursts, while there are many cases for upper limits within a few hundred seconds after the GRB time and even a few bursts (e.g. 030418 and 021004) with early afterglow detections that do not exhibit the bright, steep optical decay. In this paper, we also estimate the reverse shock emission at deceleration for these ten bursts, and discuss possible reasons for numerous non-detections.

§2 outlines the afterglow fitting and describes our method for calculating the flux and the peak frequency during the GRB. A comparison between the theoretical calculation and γ-ray observations is also described in §2. Some alternate possibilities to explain the γ-ray observations such as inverse Compton in the forward or the reverse shocks, pair enriched ejecta, or high density clumps in the circumstellar medium, are discussed in §3. In §4, we discuss reverse shock optical emission at deceleration.

2   AFTERGLOW TO γ-RAY EMISSION

The afterglow modeling is described in detail in Panaitescu & Kumar (2001) and (2002). Briefly, we determine the collimated fireball dynamics by numerical integration of a simplified set of jet propagation equations, keeping track of radiative loss of energy due to synchrotron and inverse-Compton emissions. The synchrotron peak and cooling frequencies are calculated by assuming that a certain constant fraction of the thermal energy of the shocked fluid is imparted to electrons and magnetic field. The effect of IC loss including the proper Klein-Nishina cross-section is included in the calculation of the cooling frequency. The observed lightcurves are calculated by integrating the emissivity over equal arrival time surface. All of the unknown parameters, which include jet opening angle, the total energy release in the explosion

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[1] When the outermost γ-ray producing shell undergoes deceleration and is heated by the reverse shock it produces optical flash, and its radius increases as $\sim t^{1/4}$ for $t \gtrsim t_d/4$ (where t is the observer time). Therefore, the increase in the radius for a 5-fold increase in time is less than a factor 2.

(which is is the sum of the kinetic energy given in PK02 and the energy in γ-ray radiation), the fraction of energy in electrons (ε_{ef}), and the fraction in magnetic field (ε_{Bf}), are obtained by fitting the observed light-curves and the spectrum with the theoretically calculated curves by a χ^2 minimization. The parameter ε'_{ef}, which determines the minimum thermal Lorentz factor of electrons, is 0.1 for all bursts for which $p > 2$ (PK02). Since the high energy spectral index during the burst gives $p > 2$ we set $\varepsilon'_{ef} = 0.1$ for all bursts in our calculations during the gamma-ray burst.

Using these parameters we estimate the frequency where the spectrum (νf_ν) peaks and the flux (f_ν) at this peak at deceleration (which we assume is half of the γ-ray burst duration). The results for ten bursts are summarized in Table 1 for a uniform circumburst density (wind circumburst medium had similar results, and for brevity are not listed here). The theoretical results are compared with the observed data for these bursts (see Table 1). Note that for six out of ten bursts in the table the peak frequency during the burst is within a factor of about 2 of the the observed value which we consider a reasonably good agreement. However, in four of these cases the theoretical peak flux is smaller than the observed value by an order of magnitude or more. For GRB 970508, which was a single peaked FRED burst, the fluxes are in good agreement. Therefore, for this burst the γ-ray emission could arise in an external shock; it is highly encouraging to see the forward shock model works so well to explain observations all the way from the γ-ray emission at 10s to radio at 100s of days. However, for 000301C which was also likely a single pulse FRED, and 980703 & 991208 each of which contain two simple peaks in their γ-ray light-curve and are therefore good candidates for external shock mechanism for γ-ray production, the discrepancy between theory and observation is large.

To understand how sensitive the γ-ray emission is to errors in afterglow modeling and parameter determination, and to consider some possible solutions within the framework of the external shock model, we present an analytical derivation of the main results.

The forward shock synchrotron *injection* frequency, ν_{if}, and the flux at the peak of the F_ν spectrum are (Wijers & Galama, 1999)

$$\nu_{if}(t) = \frac{0.98 q B \gamma_i^2 \Gamma}{2\pi m_e c (1+z)} \tag{1}$$

$$F_{pf}(t) = \frac{N_e P_{\nu_p} \Gamma (1+z)}{4\pi d_L^2} \tag{2}$$

where q & m_e are electron charge and mass, m_p is proton mass, $d_L = 2c\sqrt{1+z}[(1+z)^{1/2} - 1]/H_0$ is the luminosity distance, $\gamma_i = \varepsilon'_{ef}(m_p/m_e)(\Gamma - 1)$ is the minimum thermal LF of electrons (the electron distribution for $\gamma > \gamma_i$ is assumed to be a power-law of index p, i.e. $dN_e/d\gamma \propto \gamma^{-p}$), $N_e = 4\pi A R^{3-s} m_p^{-1}/(3-s)$ is the total number of swept-up ISM electrons, $\rho_0 = AR^{-s}$ is the density of the medium just ahead of the shock, Γ is the bulk LF of shocked gas,

$$B = 4c\Gamma \left[2\pi\varepsilon_{Bf}AR^{-s}\right]^{1/2}, \quad R = (4-s)c\Gamma^2 t/(1+z), \tag{3}$$

t is the observer time, and

$$P_{\nu_p} = \frac{1.04 q^3 B}{m_e c^2} \tag{4}$$

is the power radiated per electron per unit frequency, in the shell comoving frame, at the peak of the synchrotron spectrum. The numerical factors of 1.04 in the above equation and 0.98 in equation (1) are taken from Wijers and Galama (1999) for $p = 2$.

The synchrotron injection frequency and peak flux, at deceleration, for the particular cases of $s = 0$ & 2 are given below

$$\nu_{if}(t) = \varepsilon'_{ef}{}^2 \varepsilon_{Bf}^{\frac{1}{2}} \mathcal{E}_{52}^{\frac{1}{2}} (1+z)^{\frac{1}{2}} t_{d,1}^{-3/2}$$
$$\times \begin{cases} 1.01 \times 10^4 \text{ kev} & s = 0 \\ 1.7 \times 10^4 \text{ kev} & s = 2 \end{cases} \tag{5}$$

$$F_{pf}(t) = \frac{\varepsilon_{Bf}^{\frac{1}{2}} \mathcal{E}_{52}^{\frac{1}{2}}}{\left[(1+z)^{1/2} - 1\right]^2} \times \begin{cases} 1.8 \mathcal{E}_{52}^{\frac{1}{2}} n_0^{1/2} \text{ mJy} & s = 0 \\ \frac{4.2 \times 10^3 A_*}{[t_d/(1+z)]^{1/2}} \text{ mJy} & s = 2 \end{cases} \tag{6}$$

where $A_* = A/(5 \times 10^{11})$ g cm^{-1}, $\mathcal{E}$ is the isotropic equivalent of energy release in the explosion, t_d is the observer frame deceleration time in seconds, and an integer subscript n on a variable X, X_n, means $X/10^n$. In the derivation of the above equations we substituted for Γ using the equation $4\pi A R^{3-s} c^2(\Gamma^2 - 1)/(3-s) = \mathcal{E}/2$ at deceleration which states that half of the original kinetic energy of the explosion ($\mathcal{E}/2$) is deposited into swept-up ISM; the LF at deceleration is given by:

$$\Gamma_{d,2} = \begin{cases} 4.17 \left(\frac{\mathcal{E}_{52}}{n_0}\right)^{1/8} \left[\frac{(1+z)}{t_d}\right]^{3/8} & s = 0 \\ 0.74 \left[\frac{(1+z)\mathcal{E}_{52}}{A_* t_d}\right]^{1/4} & s = 2 \end{cases} \tag{7}$$

We next calculate the electron cooling frequency. For this we need the Compton Y parameter, defined as $Y \equiv \tau_T \int d\gamma_e \gamma_e^2 (dn_e/d\gamma_e)$, with τ_T being the column density of electrons times the Thomson cross-section. The Y-parameter is obtained by solving the equation describing the radiative loss of energy -

$$\frac{d}{dt'}\left[m_e c^2 \gamma_e \frac{dn_e}{d\gamma_e}\right] = -\frac{dn_e}{d\gamma_e} \frac{(1+Y)\sigma_T B^2 \gamma_e^2 c}{6\pi}, \tag{8}$$

where t' is the comoving time, B is the magnetic field which we assume is uniform, and σ_T is the Thomson scattering cross-section. Consider the comoving frame down-stream fluid velocity to be v. This relates t' and the comoving radial coordinate r' viz. $dr' = v\,dt'$. Changing the independent variable from t' to r' and integrating the above equation over the electron distribution we find

$$\frac{d(\varepsilon_e U)}{dr'} = -\frac{(1+Y)\sigma_T B'^2 c n_e \overline{\gamma_e^2}}{6\pi v}, \tag{9}$$

where U is the thermal energy density of shocked fluid, and $\overline{\gamma_e^2}$ is the average γ_e^2. Integration of this equation over r' for a highly relativistic shock ($v \sim c$) and highly radiative fluid ($\nu_i \gg \nu_c$) we find

$$Y(1+Y) \approx \frac{\varepsilon_e}{4\varepsilon_B}. \tag{10}$$

The calculation of the cooling LF of electrons, γ_c, at deceleration, is straightforward and is given below; γ_c is the LF of electrons that lose their energy in a time available since crossing the shock front averaged over the population, given by $t_c \sim t_d/3^{(2-s)/2}$.

$$\gamma_c(t_d) = \frac{3\pi m_e c(1+z)}{2\sigma_T B'^2 t_c \Gamma_d (1+Y)} =$$
$$\frac{3(1+z)^{1-s} m_e \Gamma_d^{2s-3}}{64\sigma_T \varepsilon_B A c(4ct_d)^s t_c (1+Y)} \qquad (11)$$

This in turn is used to calculate the synchrotron frequency, in observer frame, corresponding to the LF γ_c, and is referred to as the cooling frequency (ν_c).

$$\nu_c(t_d) = \frac{qB'\gamma_c^2 \Gamma_d}{2\pi m_e c(1+z)}$$

$$\text{or} \quad \nu_c(t_d) = \begin{cases} \frac{3.2}{(\mathcal{E}_{52} t_d (1+z)\varepsilon_B)^{1/2}\varepsilon_e n_0} & \text{ev} & s=0 \\ 2.2 \times 10^{-7} \frac{(\mathcal{E}_{52} t_d)^{1/2}}{\varepsilon_B^{1/2} A_*^2 \varepsilon_e (1+z)^{3/2}} & \text{ev} & s=2 \end{cases} \quad (12)$$

where we have made use of equations (7), (10), and (11). We see that the cooling frequency at deceleration is typically much smaller than the synchrotron injection frequency (see eq. 5) and thus the peak of the νf_ν spectrum will generally be at ν_{if}. For the case where $\nu_{if} > \nu_c$, the flux at the peak of the νf_ν spectrum is obtained by using equations (5), (6) & (12) and is given here

$$F_{\nu_p}(t_d) = \frac{(\mathcal{E}_{52} t_d)^{1/2}(1+z)^{-1/2}}{\varepsilon'_{ef}\varepsilon_{ef}^{1/2}\left[(1+z)^{1/2}-1\right]^2}$$
$$\times \begin{cases} 6 \times 10^{-4} \text{ mJy} & s=0 \\ 3.5 \times 10^{-4} \text{ mJy} & s=2 \end{cases} \quad (13)$$

Note that the flux is independent of ε_B and the density of the ISM – the two parameters that have the largest error associated with them in afterglow modeling (PK02). Using equations (5) and (13) we calculate the peak frequency and the flux during the γ-ray burst and the results are in good agreement with the numerical calculation result presented in table 1.

Table 1 shows that for all those bursts for which the observed and theoretical peak frequencies agree within a factor of two[2] (6 cases altogether), the theoretically calculated fluxes, with the exception of 970508, are too small by an order of magnitude compared to the observed fluxes.

We see from equation (13) that the flux at the peak of νf_ν depends only on $\mathcal{E}$, which is a very well determined parameter, and ε'_{ef} which is 0.1 for all the bursts with $p > 2$, and therefore there is no way to reconcile the difference between the observed flux and the theoretical expectation in the simplest version of the synchrotron emission in the external shock model. Any error in the parameter determination from afterglow modeling does not affect our calculation of the γ-ray flux. In other words, even if we consider ε_{Bf} and the ISM density n during the burst to take on values completely unrelated to what is determined from afterglow modeling the observed flux cannot be reconciled with the theoretical expectations in the forward shock model. This is a very robust result and effectively rules out synchrotron origin for γ-ray emission in the external shock model for these bursts.

In four cases, viz. 980519, 980703, 990123 & 000418, the theoretically calculated peak frequencies are much smaller than the observed value; these are the four cases with the smallest ε_{Bf} as determined by the afterglow modeling (see Table 1). Could a larger ε_{Bf} at early times, as in the case of 021211 (Kumar & Panaitescu, 2003, hereafter KP03), explain the peak frequencies for these four cases? If ε_{Bf} were to be 0.5 during the burst for 980519 & 000418 we can explain the γ-ray emission for these GRBs. However, even if we set $\varepsilon_{Bf} = 1$ during the burst for 980703 & 990123 the synchrotron frequency falls short of the observed value. Could the gamma-ray burst in these cases arise as a result of inverse-Compton (IC) scattering of the synchrotron radiation in the forward or the reverse shock? We consider this possibility, and some others, in the next section. We also investigate whether the peak flux of the IC component might be able to match the observed flux for the other five bursts which have too small synchrotron flux.

3   GAMMA-RAYS IN EXTERNAL SHOCK: SOME ALTERNATE POSSIBILITIES

We consider below (§3.1) a combination of synchrotron and inverse-Compton processes in the forward and reverse shocks to determine if this could explain the γ-ray emission properties for the nine "problem bursts" in our sample of ten discussed in the last section. In §3.2 we discuss if a collision between the GRB ejecta and a high density clump might be able to explain the large γ-ray flux for the five of the bursts in our sample, and in §3.3 we look into the effect of electron-positron pair loaded ejecta on γ-ray emission.

3.1   Inverse Compton in the external shock

We investigate the effect of IC in external shocks – forward as well as the reverse shock – to see if the observed γ-ray emission for the bursts in our sample could be explained by the IC process.

Consider the flux at the peak of the synchrotron radiation νf_ν spectrum, ν_p, to be f_{ν_p}. We consider inverse-Compton scattering by a population of electrons that could be distinct from the population that gives rise to the synchrotron radiation. For instance, the synchrotron emission could be produced in the reverse shock (RS) and the IC scattering in the FS. Let us take the minimum thermal LF of electrons in the IC-scattering region to be $\gamma_{min} = \min(\gamma_i, \gamma_c)$, the electron distribution to have a break at $\gamma_b = \max(\gamma_i, \gamma_c)$ such that for $\gamma > \gamma_b$ the electron distribution is proportional to γ^{-p-1}; γ_i & γ_c are the injection and cooling LFs for electrons. The peak of the IC radiation (for νf_ν) is at

$$\nu_p^{IC} \sim \nu_p \gamma_b^2. \qquad (14)$$

If the optical depth of the medium to Thomson scattering is τ_T, then the flux at the peak for the case where $\gamma_i \ll \gamma_c$ is

$$f_{\nu_p}^{IC} \sim \tau_T (\gamma_{min}/\gamma_b)^{p-1} f_{\nu_p}. \qquad (15)$$

For $\gamma_c < \gamma_i$, there is a slightly different relationship.

The optical depth at deceleration in the forward shock is given by

Table 1. Forward Shock Emission at Deceleration For Homogeneous External Medium

Burst	$\mathcal{E}$ ($\times 10^{52}$ ergs)	ε_{Bf}	$\nu_p(t_d)$ (keV)	$\nu_{p,obs}$ (keV)	$f_{\nu_p}(t_d)$ (mJy)	$f_{\nu_p,obs}$ (mJy)	Refs.
970508	7.92	4.5×10^{-2}	98.4	100	0.51	0.6	2,4
980519[a]	99.8	3.5×10^{-5}	7.0	700	1.25	0.3	3,4
980703	0.40	3.0×10^{-3}	0.8	370	0.21	0.3	3
990123	277.5	9.9×10^{-4}	6.6	780	1.24	9.0	1,2,3,5
990510	55.5	5.0×10^{-3}	184.9	160	0.27	4.0	1,2,3
991208	11.9	3.8×10^{-2}	118.7	190	0.78	20.0	1,3,6
991216	100.0	6.2×10^{-3}	153.4	410	1.0	30.0	1,3
000301c	8.19	1.0×10^{-1}	541.6	500[b]	0.04	0.3	1,3,7
000418	8.05	1.6×10^{-2}	25.2	280	0.32	0.4	1,3
000926	39.7	8.1×10^{-2}	198.4	130	0.21	0.7	1

$\varepsilon'_{ef} = 0.1$, $\varepsilon_{ef} = 0.5$ for all bursts, n_0, θ_0 are equal to values found from afterglow modeling.

References: (1) Mazets (personal communication); (2) Amati, L. et al. 2002; (3) Jiminez, R. et al. 2001; (4) Nicastro, L. et al 1999; (5) Briggs, M. S. et al 1999; (6) Hurley, K. et al 2000; (7) Smith, D. A. et al 2002

[a] Redshift not known for this burst, $z = 1$ used.
[b] No $\nu_{p,obs}$ available for this burst; a value of 500 kev assumed.

$$\tau_T = \frac{\sigma_T \mathcal{E}}{4\pi m_p c^2 \Gamma_0^2 R_d^2}, \tag{16}$$

where $R_d = (4-s)ct_d \Gamma_d^2/(1+z)$ is the deceleration radius, Γ_d is the LF at deceleration, and $\Gamma_0 \sim 1.5\Gamma_d$ is the initial LF of the ejecta (see eq. 19). Using equation (7) this can be rewritten as follows

$$\tau_T = \begin{cases} 3.9 \times 10^{-9} n_0^{3/4} \mathcal{E}_{52}^{1/4} [t_d/(1+z)]^{1/4} & s = 0 \\ 8.7 \times 10^{-4} A_*^{3/2} \mathcal{E}_{52}^{-1/2} [(1+z)/t_d]^{1/2} & s = 2 \end{cases} \tag{17}$$

We see that the optical depth for a uniform density ISM is very small, and therefore the inverse Compton flux due to scattering in the forward shock region, for $s = 0$, is likely to be too small to be observationally interesting.

The optical depth to Thomson scattering of the ejecta at deceleration can be obtained directly from equation (17) by recognizing that the mass of the ejecta is larger than the swept-up ISM mass by a factor Γ_d. Thus,

$$\tau_T = \begin{cases} 1.5 \times 10^{-6} n_0^{5/8} \mathcal{E}_{52}^{3/8} [t_d/(1+z)]^{-1/8} & s = 0 \\ 5.4 \times 10^{-2} A_*^{5/4} \mathcal{E}_{52}^{-1/4} [(1+z)/t_d]^{3/4} & s = 2 \end{cases} \tag{18}$$

3.1.1 Reverse Shock Break Frequencies and Peak Flux

To complete the calculation of inverse Compton scattering of synchrotron emission produced in the reverse shock (RS) region we provide below the synchrotron characteristic frequency and the flux from the RS (see KP03 for details).

The thermal energy per proton in the RS at deceleration, e_p, can be calculated using the following pair of equations

$$e_p = \frac{1}{2}\left(\frac{\Gamma_d}{\Gamma_0} + \frac{\Gamma_0}{\Gamma_d}\right), \quad \frac{\Gamma_d}{\Gamma_0} = \left[1 + 2\left(\frac{n_0\Gamma_0^2}{n_{ej}}\right)^{1/2}\right]^{-1/2}. \tag{19}$$

which fits the results of numerical calculations to better than 8% in the Newtonian, Relativistic and intermediate regimes; where n_{ej} is the comoving density of the ejecta, n_0 is the ISM density, and Γ_0 is the initial LF of the ejecta.

It can be shown that n_{ej}/n_0 at the time when the reverse shock arrives at the back end of the ejecta (which is approximately equal to the deceleration time for the ejecta) is $1.5\Gamma_0^2$ for a uniform density ISM and $3.5\Gamma_0^2$ for $s = 2$ medium. The reverse shock in this case is neither highly relativistic nor Newtonian. Using the above equation we find the thermal energy per proton in the RS in this case to be $0.13m_p c^2$ ($0.067m_p c^2$) for a $s = 0$ ($s = 2$) medium.

The injection frequency at deceleration for RS is smaller than the FS by a factor of $\Gamma_d^2/0.13^2$ for uniform ISM and is given below

$$\nu_{ir}(t_d) = \frac{0.07qm_p^{5/2}\varepsilon_{Br}^{1/2}\varepsilon_{er}'^2 n_0^{1/2} R_d^{-s/2}\Gamma_d^2}{(2\pi)^{1/2} m_e^3(1+z)}. \tag{20}$$

This equation, and a similar one for $s = 2$, can be rewritten as

$$\nu_{ir}(t_d) = \varepsilon_{Br}^{1/2}\varepsilon_{er}'^2$$
$$\times \begin{cases} 37\, n_0^{1/4}\mathcal{E}_{52}^{1/4}(1+z)^{-1/4}t_d^{-3/4}\ \text{ev} & s = 0 \\ 610\, A_*^{1/2}t_d^{-1}\ \text{ev} & s = 2 \end{cases} \tag{21}$$

where we have used equation (7) to eliminate Γ_d. The cooling frequency in the reverse shock region, when $\nu_{ir} > \nu_{cr}$, is given by equation (12) with appropriate values of ε_B and ε_e' for the reverse shock. However, the reverse shock ν_{cr} is typically larger than ν_{ir} (see Table 2), so equation (10) is not a valid approximation for the Compton Y parameter any longer and we must also use an appropriately modified form version of equation (12).

The flux at the peak of the reverse shock f_ν spectrum at deceleration is larger than the peak flux from the FS by a factor Γ_d and can be written as

$$F_{pr}(t_d) = \frac{(3\varepsilon_{Br}A)^{1/2}\, q^3 \mathcal{E}(1+z)^{s/2}}{m_e m_p c^3 d_L'' \Gamma_d^{s-1}\, (4ct_d)^{s/2}\, [(3-s)\,\pi]^{1/2}} \tag{22}$$

or

$$F_{pr}\left(t_d\right) = \frac{\varepsilon_{Br}^{1/2}}{[(1+z)^{1/2}-1]^2}$$

$$\times \begin{cases} 6.8 \times 10^2 (1+z)^{3/8} \mathcal{E}_{52}^{9/8} n_0^{3/8} t_d^{-3/8} \text{ mJy} & s=0 \\ 2.7 \times 10^5 (1+z)^{3/4} \mathcal{E}_{52}^{3/4} A_*^{3/4} t_d^{-3/4} \text{ mJy} & s=2 \end{cases} \quad (23)$$

The self-absorption frequency in the reverse shock region, ν_{Ar}, is often as large as the cooling and the injection frequencies, and therefore should be taken into consideration in the calculation of observed flux. The self-absorption and cooling frequencies and the Compton Y parameter need to be calculated together in a self-consistent way (as we do for all of our numerical calculations). However, when electron cooling is dominated by the inverse-Compton scattering and $\max\{\nu_{ir}, \nu_{cr}\} > \nu_{Ar}$, the calculation of self-absorption frequency is considerably simplified and is given by (KP03)

$$\nu_{Ar}\left(t_d\right) \left(\frac{\nu_{ir}}{\nu_{Ar}}\right)^{\alpha/2} = \left(\frac{\varepsilon_{Br}}{\varepsilon'_{er}}\right)^{1/2}$$

$$\times \begin{cases} 8.4 \times 10^{-2} \mathcal{E}_{52}^{3/8} n_0^{3/8} t_d^{-5/8} (1+z)^{-3/8} \text{ ev} & s=0 \\ 49 \, A_*^{3/4} t_d^{-1} \text{ ev} & s=2 \end{cases} \quad (24)$$

where α depends on the ordering of ν_{ir}, ν_c and ν_{Ar}, and is equal to 1/3 if $\nu_c > \nu_{ir} > \nu_{Ar}$, and $-p/2$ when $\nu_c > \nu_{Ar} > \nu_{ir}$.

3.1.2   Inverse Compton results

The peak frequency and flux for the IC radiation is calculated as described in §3.1. The calculation of the synchrotron injection frequency is straightforward & is carried out as described in §2 for the FS and §3.1.1 for the RS. The synchrotron self-absorption frequency is typically small in the FS and is unimportant for IC calculation. However, in the RS the self-absorption can be larger than the cooling frequency and these frequencies must be calculated self-consistently; we calculate these frequencies numerically.

There are four cases of the IC scattering to consider: synchrotron in the FS and IC in either the FS or the RS, synchrotron in RS and IC in the RS or the FS. We have investigated these cases numerically, and we have explored the parameter space $-\mathcal{E}, \varepsilon_{Br}, \varepsilon'_{er}, \varepsilon_{Bf}, \varepsilon'_{ef}, n-$ for each burst to determine if the observed γ-ray peak frequency and flux could be explained by the IC radiation, either for a uniform density circum-burst medium or a wind-like medium ($\rho \propto R^{-2}$). The results for each burst are described below.

For a uniform density ISM the synchrotron-IC mechanism in external shock offers a vanishing parameter space that is consistent with the gamma-ray emission properties for GRB 990123. However, for a $s=2$ medium we find some solutions where the synchrotron emission produced in the forward shock undergoes inverse-Compton scattering in the reverse-shock region. The density required for these solutions is $\sim 10^2$ times that normally associated with Wolf-Rayet star winds, and much greater than what is found from modeling of early and late time afterglow observations. Other parameters such as the energy in the explosion, micro-physics shock parameters in the forward and the reverse shock are roughly consistent with the afterglow observations. However, the low energy spectral index for the γ-ray spectrum (α) is -0.5 whereas the observed index is 0.4. Therefore, we do not have a fully self consistent solution for

the gamma-ray emission properties for 990123 in the external shock model. This is surprising in the light of the arguments for external shock (see §1) for this burst, and perhaps suggests that there may be some other mechanism producing the γ-ray photons that is completely different from the standard internal/external shocks model. In the next subsection we explore if high density gas near the deceleration radius could explain the γ-ray emission.

In the case of 980519 there are IC solutions for $s=2$ medium where the synchrotron radiation is produced in the forward shock & IC in the reverse-shock, and the parameter space consists of A_* in the range of 15 to 100 which is at least a factor of a few larger than the value of $A_* \sim 3.5$ determined from afterglow modeling. However, the IC solution requires $\varepsilon_B \sim 10^{-4}$ in the forward shock that is much smaller than the value of 0.1 we find for this burst from the afterglow fitting when $s=2$. The RS optical peak flux of $\sim$ 11th magnitude is perhaps not a problem for this solution.

For 980703 there are solutions found for $s=0$. However, these solutions require $\mathcal{E} > 10^{55}$ erg and the RS optical flux is larger than 1 Jy, and therefore these are not acceptable solutions. The solutions we find for this burst with $s=2$, which involve synchrotron in the FS and IC in the RS, require $A_* \gtrsim 5$ and other parameters are roughly consistent with the values we find from the afterglow modeling; the optical flux from the RS is $\sim$ 20 mJy. If we ignore the somewhat high density requirement, this burst could perhaps be produced as IC in the external shock.

For 990510 no solution is found that is in agreement with the observed properties of this burst. The same is true for 991208, 991216. To be precise, there are no solutions found when the density of the medium is taken to be uniform. However, for a pre-ejected wind medium there are regions in the multidimensional parameter space $(\mathcal{E}, A_*, \varepsilon_B, \varepsilon'_e)$ that give gamma-ray flux and peak frequency in agreement with observations for these bursts where synchrotron emission is produced in the forward shock and the inverse-Compton scattering takes place in the reverse shock region. The problem is that for all of these "solutions" A_* is greater than about 10^2 which is larger than what we obtain from afterglow modeling by two orders of magnitude, and too large for winds from Wolf-Rayet stars. Moreover, the large ε_{Br} in the reverse shock for these solutions gives rise to optical R-band flux of about 10 Jy, or 6th magnitude, which is unlikely to have gone unnoticed. Therefore we do not consider these solutions physically acceptable.

We find two different IC "solutions" for 000418 for a $s=2$ circum-burst medium; one of which is synchrotron in the FS and IC in the RS, and the other is synchrotron in the RS and IC in the FS. The first scenario requires $A_* \gtrsim 25$ (which is larger by factor $\sim 10^2$ than determined from afterglow observations) and ε_{Bf} is between $\sim 10^{-5}$ and 2×10^{-4} which is smaller by two orders of magnitude than the value we find from afterglow modeling. The peak optical flux from the RS is between 20 mJy and 3 Jy; the lower flux value in this case certainly poses no difficulty with observations. The latter scenario requires $A_* \gtrsim 400$ and $\varepsilon_{Br} \sim 10^{-5}$ which are unlikely to be realized in nature.

There are also two solutions for 000301c with $s=2$. For FS synchrotron & IC scattering in the RS, A_* is about an order of magnitude larger than that found by afterglow modeling, but the optical flux from RS is not a problem, being

$\lesssim 0.5$ Jy. The magnetic field parameter in the forward shock required for the IC solution is, however, several orders of magnitude smaller compared with the value we find from afterglow modeling in a wind-like medium for this burst. This together with the required high density for the CBM makes this solution unacceptable. For the case of RS synchrotron & IC scattering in the FS, the allowed parameter space to explain the γ-ray observations require the energy to be a factor of 10 smaller than the observed value, and $A_* \gtrsim 100$. The magnetic field parameter is also 100 times smaller than the afterglow value, so we do not consider these solutions viable. For a uniform density medium the IC solution for 000301c requires $\mathcal{E} > 10^{55}$ which is more than two orders of magnitude larger than the energy determined from either the γ-ray fluence or the afterglow emission. The situation for 000926 is a bit worse than 000301c.

We also note that the IC flux for 970508, in any of the four possible combinations, at the observed peak is too small to be a significant contributor to the observed flux.

3.2   Effect of density clumps in the ISM on gamma-ray flux

In this subsection we investigate whether a dense clump of gas in the circum-burst medium (CBM) might increase the flux in the γ-ray band and thereby explain flux observations at the peak of the νf_ν spectrum for some of the bursts in our sample.

Consider a dense clump of angular size greater than Γ_0^{-1}, and proton number density n; Γ_0 is the initial Lorentz factor (LF) of the ejecta which we assume does not decrease until it runs into the clump. For the calculation of radiation such a clump can be treated as a spherical object. We take the external density to be sufficiently high that the forward shock LF is less than Γ_0 and the reverse shock is relativistic; the parameter $\xi \equiv \Gamma_0^2 n / n_{ej} > 1$ determines the thermal LF of protons in the forward and the reverse shocks; n_{ej} is the density of the ejecta when it hits the clump. For large n the thermal LF of protons in the FS is $\gamma_{p,f} = \Gamma_0 \xi^{-1/4}/2^{1/2}$ and in the RS it is $\xi^{1/4}/2^{1/2}$.

The thermal energy density in these shock regions is $4 n m_p c^2 \gamma_{p,f}^2 \sim n \Gamma_0^2 m_p c^2 \xi^{-1/2}$, and therefore the magnetic field strength $B \propto (\varepsilon_{Bf} n)^{1/2} \Gamma_0 \xi^{-1/4}$. The synchrotron injection frequency in the forward shock is $\nu_i \propto \varepsilon_{ef}'^2 (\varepsilon_{Bf} n)^{1/2} \Gamma_0^4 \xi^{-1}$.

The number of swept up protons at deceleration is obtained by equating the thermal energy of protons (in lab frame) with half the energy in the explosion i.e., $N_p m_p c^2 \gamma_{p,f}^2 = \mathcal{E}/2$ or $N_p = \mathcal{E}\xi^{1/2}/(m_p c^2 \Gamma_0^2)$.

Let us assume that the distance of the clump from the center of the explosion is R_c and the forward shock travels a distance of δR_c before the shocked material acquires half the energy of the explosion. Therefore, $N_p = 4\pi n R_c^3 \delta = \mathcal{E}\xi^{1/2}/(m_p c^2 \Gamma_0^2)$. The GRB duration (in the observer frame), if the γ-rays are produced due the ejecta colliding with the dense clump, is $t_\gamma \sim R_c/(c\gamma_{p,f}^2) \sim R_c \xi^{1/2}/(c\Gamma_0^2)$. Combining this with the equation for N_p we find: $n\Gamma_0^8 \sim \xi^2 \mathcal{E}/(4\pi m_p c^5 t_\gamma^3 \delta)$. Substituting this back into the equation for injection frequency we find $\nu_i \propto \varepsilon_{Bf}^{1/2} \varepsilon_{ef}'^2 \mathcal{E}^{1/2} t_\gamma^{-3/2} \delta^{-1/2}$.

The time scale in the lab frame for electrons to cool in the forward shock is $\sim \delta R_c/(c\gamma_{p,f})$, from which we cal-

culate the cooling frequency to be $\nu_c \propto (n\varepsilon_{Bf})^{-3/2}(1+Y)^{-2}(\delta R_c)^{-2} \propto \varepsilon_{Bf}^{-3/2}(t_\gamma \mathcal{E})^{-1/2} n^{-1}\delta^{-3/2}(1+Y)^{-2}$.

The flux at the peak of the synchrotron spectrum is $f_p \propto \varepsilon_{Bf}^{1/2} n^{1/2}\mathcal{E}$. For $\nu_c < \nu_{if}$, expected for a high density clump, the Compton Y-parameter is $\sim (\varepsilon_{ef}/\varepsilon_{Bf})^{1/2}$, and the flux at the peak of νf_ν i.e. at ν_{if} is proportional to $\mathcal{E}^{1/2} t_\gamma^{1/2}\delta^{-1/2}\varepsilon_{ef}^{-1/2}\varepsilon_{ef}'^{-1}$. Note a weak dependence of the peak flux on $\delta \equiv \delta R_c/R_c$.

The distance δR_c the FS moves before the GRB ejecta is decelerated is obtained by calculating the density of the ejecta at R_c; $n_{ej} \sim \mathcal{E}/[4\pi R_c^2 m_p c^2 \Gamma_0^2 \max(t_* c, R_c/\Gamma_0^2)]$, where t_* is the duration of the central engine in the lab frame. Using this expression and the definition of ξ we find that $\delta \sim \max(t_*/t_\gamma, \xi^{-1/2})$.

Since the peak flux is proportional to $\delta^{-1/2}$, a factor of ten increase in the flux requires $\xi \gtrsim 10^4$ or the clump density $n \sim n_{ej}(10^{-4}\Gamma_0^2)$. Therefore, for $\Gamma_0 \sim 10^2$, n is of order n_{ej} and we find that in order to explain the gamma-ray flux in the clump-ejecta collision the density of the clump needs to be similar to the ejecta as in the internal shock model! Very bright early afterglow will be produced in such a collision which might pose a problem for this scenario. We note that the increase in the flux is accompanied by an increase in the peak frequency, both of which are proportional to $\delta^{-1/2}$, but the latter quantity can be easily adjusted by a decrease in ε_{Bf} or ε_e' to match the observations.

3.3   Effect of $e^\pm$ pairs present in the ejecta

In this subsection we consider whether $e^\pm$ pairs present in the ejecta can make inverse-Compton radiation match the peak flux and frequency at deceleration. Pairs would soften the reverse shock spectrum, and the larger optical depth could increase IC flux at the peak. Adding $N_\pm$ pairs per proton to the ejecta increases the number of radiating particles in the reverse shock region thus lowering the energy per particle. This decreases ν_{ir} by a factor of $N_\pm^2$ while increasing the peak flux of the f_ν spectrum by a factor of $N_\pm$. The cooling frequency for the highly radiative regime is not affected, nor is it changed when the Compton-Y parameter is much less than one; it is, however, affected when $\nu_{ir} < \nu_{cr}$ (more common in the reverse shock emission than $\nu_{ir} > \nu_{cr}$, see Table 2) and $Y > 1$, increasing it by a factor $N_\pm^{2(p-2)/(4-p)}$.

The flux at the cooling frequency, which is the peak of the reverse shock synchrotron νf_ν spectrum, is proportional to $N_\pm^{3(2-p)/(4-p)}$. We see that for $p = 2$ the cooling frequency and the peak flux are independent of $N_\pm$. The peak flux increases by a factor of $N_\pm^{3/5}$ for $p = 1.5$ (decreasing for $p > 2$). For inverse-Compton scattering of these reverse shock synchrotron photons by the ejecta, the IC peak, $\nu_{p,IC} = \gamma_c^2 \nu_c$, will increase by a factor of $N_\pm^{4(p-2)/(4-p)}$. We see again that $\nu_{p,IC}$ is not affected when $p = 2$, but can go up ($p > 2$) or down ($p < 2$) for other values. The IC flux at the peak changes by a factor of $N_\pm^{6(2-p)/(4-p)}$ (from its value without pairs present), which, similarly, does not change much for values of p around 2. The IC peak flux decreases for $p > 2$ and at most, can be increased by a factor of $\sim N_\pm$ when the electron distribution is very hard, i.e. $p \lesssim 1.5$.

It can be shown that the peak flux for synchrotron produced in the FS and IC in the slow cooling RS (with $Y \gg 1$)

is proportional to $N_{\pm}^{3(2-p)/(4-p)}$, decreasing for $p > 2$. If the RS was in the highly radiative regime, the IC flux would increase as $N_{\pm}^2$; however, the injection frequency decreases rapidly as $N_{\pm}^{-2}$, whereas ν_{cr} is independent of $N_{\pm}$ in the fast cooling regime. We therefore expect ν_{ir} to become less than ν_{cr} as $N_{\pm}$ becomes larger than a certain value and the slow cooling regime considered earlier once again applies. The reverse process – synchrotron in the RS and IC in the FS – has also lower peak flux for $p > 2$. Thus, we find that pairs present in the ejecta are not likely to be able to account for the theoretical IC and observed γ-ray flux difference.

4   EARLY AFTERGLOW EMISSION

It is generally believed that the steeply falling off early afterglow emission observed from GRBs 990123 and 021211 was produced by the reverse shock heated ejecta from the explosion. This emission falls off roughly as $t^{-1.7}$ and flux falls below the forward shock emission level after about $10-20$ minutes. We use the equations in §3.3 to calculate the observed flux in the optical R-band at deceleration for this sample of 10 bursts. For the case of $\nu_{ir} < \nu_{cr} < \nu_R$, the flux at $\nu_R \sim 2$ eV, the R-band in observer frame, is given by

$$f_R(t_d) = \frac{\varepsilon_{Br}^{\frac{p}{4}}\varepsilon_{er}'^{\,p-1}\varepsilon_{er}^{-\frac{1}{2}}}{[(1+z)^{1/2}-1]^2}$$

$$\times \begin{cases} 400 \times 3.3^{\frac{p-1}{2}}(1+z)^{\frac{2-p}{8}}\mathcal{E}_{52}^{\frac{p+6}{8}}n_0^{\frac{p-2}{8}}t_{d,1}^{-\frac{3p+2}{8}} \text{ mJy} & s=0 \\ 584 \times 30^{\frac{p-1}{2}}\mathcal{E}_{52}A_*^{\frac{p-2}{4}}t_{d,1}^{-\frac{p}{2}} \text{ mJy} & s=2 \end{cases} \quad (25)$$

Whereas for the case where $\nu_{ir} < \nu_R < \nu_{cr}$ the flux is

$$f_R(t_d) = \frac{\varepsilon_{Br}^{\frac{p+1}{4}}\varepsilon_{er}'^{\,p-1}}{[(1+z)^{1/2}-1]^2}$$

$$\times \begin{cases} 290 \times 3.3^{\frac{p-1}{2}}(1+z)^{\frac{4-p}{8}}\mathcal{E}_{52}^{\frac{p+8}{8}}n_0^{\frac{p+2}{8}}t_{d,1}^{-\frac{3p}{8}} \text{ mJy} & s=0 \\ 4.8\text{x}10^4 \times 30^{\frac{p-1}{2}}\mathcal{E}_{52}^{\frac{3}{4}}A_*^{\frac{p+2}{4}}t_{d,1}^{-\frac{2p+1}{4}}(1+z)^{-\frac{3}{4}} \text{ mJy} & s=2 \end{cases} \quad (26)$$

In Table 2, we provide the theoretical estimations of the magnitude of the reverse shock emission for the ten bursts in our sample (for a homogeneous external medium and assuming the RS parameters to be same as the FS), to determine if these bursts would have had a bright optical flash. These results were obtained numerically using an accurate calculation of the cooling and the self-absorption frequencies, which can also be found in Table 2, and the flux is found to be consistent with the analytical estimate given above. Our fluxes are somewhat smaller than reported in Soderberg & Ramirez-Ruiz (2002). The difference is perhaps because the RS falls in a regime that is neither Newtonian nor relativistic where the usual asymptotic approximations are not very accurate, and one needs a more accurate calculation for this intermediate case (Nakar & Piran 2004 have made a similar point).

We see that for six of the ten bursts the optical flux is between 8.5 and 11-th magnitude, and the cooling frequency at deceleration is small (less than or of order the R-band frequency). With the cooling frequency either below or dropping below the optical rather quickly, and no electrons left in the RS capable of radiating in the optical band, we would not see the expected $\sim 1/t^2$ falloff, but a

Table 2. Predicted reverse shock flux using afterglow parameters for homogeneous external medium

Burst	R^a	ν_{ir} (eV)	ν_{cr} (eV)	ν_{ar} (eV)
970508	9.8	1.0×10^{-2}	5.8	3.9×10^{-2}
980519[b]	17.1	3.8×10^{-4}	5.1×10^5	2.8×10^{-3}
980703	17.4	2.4×10^{-5}	6.0×10^1	2.0×10^{-3}
990123	14.4	5.3×10^{-4}	5.1×10^4	2.1×10^{-3}
990510	11.9	3.1×10^{-4}	3.2×10^1	1.2×10^{-2}
991208	8.8	1.0×10^{-2}	2.0×10^{-2}	1.0×10^{-1}
991216	8.5	1.7×10^{-4}	3.0×10^{-2}	7.0×10^{-2}
000301c	10.8	2.0×10^{-2}	7.0×10^{-3}	1.2×10^{-1}
000418	10.9	5.0×10^{-3}	7.9×10^{-1}	4.5×10^{-2}
000926	9.5	3.5×10^{-2}	1.5×10^{-1}	1.4×10^{-1}

[a] Reverse shock R-band magnitude at deceleration with parameters determined from afterglow modeling.
[b] Redshift not known for this burst, $z = 1$ used.

more rapid falloff of $\sim 1/t^3$ (Kumar & Panaitescu, 2000). This falloff is fast, but even so, some of these bright optical transients could be seen for a few hundred seconds by rapid followup observations with a limiting magnitude of $R \sim 15$.

The remaining four have much fainter optical emission and large cooling frequency. The magnetic field parameter determined from afterglow modeling for these bursts is much lower than those with bright reverse shock emission. With the high cooling frequency (at least a factor of 10 above the observing band frequency of 2 eV), we expect this emission to exhibit t^{-2} falloff; however, this faint emission may be hidden by brighter forward shock afterglow emission.

For those bursts which are fit equally well in an $s = 2$ medium (970508, 000418, 991208, 000301c, 991216), the reverse shock flux at deceleration has been calculated using the afterglow parameters in PK02. We find that the flux is typically a few times larger in the s=2 model than uniform ISM case discussed above.

According to table 2, the peak R magnitude for the reverse shock emission for 990123 is 14.4 (using the forward shock values for all parameters in the reverse shock) whereas the observed peak flux was $R = 8.9$ (Akerlof et al. 1999). This suggests, as has been pointed out by Zhang et al. 2003, that ε_B was larger in the RS by a factor of about 10^2 than in the FS. Since $\nu_c \propto \varepsilon_B^{-3/2}$, by making $\varepsilon_{Br} = 0.07$, the cooling frequency has been lowered from 51 keV to 100 eV. The R band is at about 2 eV, so the cooling frequency is still well above the optical at deceleration, allowing for the $\sim 1/t^2$ falloff that was observed.

Bursts with small optical flux at deceleration have small ε_B and/or ε_e' in the RS and their cooling frequency is generally high, allowing the optical emission falling off as $\sim 1/t^2$ to occur. If ε_B in the RS for these bursts were larger than the FS, as found for 990123 (Zhang et al. 2003) & 021211 (KP03), the flux will be boosted to levels comparable to that of the other brighter bursts.

Besides 990123 and 021211 there have been no observations of a bright and quickly fading early afterglow for any other bursts. There have been some early (time since onset of burst < 0.01 day or ~ 10 minutes) detections in

the optical, for example 030329 and 021004, but the emission was not falling off as $\sim 1/t^2$. There have been about 18 bursts with upper limits published in the GCN Circulars (Barthelmy et al. 1995) and in the literature (e.g. Akerlof et al. 2000, Kehoe et al. 2001), for emission between the GRB time and 0.01 day (9 of these bursts reported in the GCNs had later optical afterglow detections). Searching the GCN Circulars with the GRBlog website (Quimby et al. 2003), we find that the burst upper limits range from $R \sim 10$ for 030115 (Castro-Tirado et al. GCN 1826) at early times to $R \sim 20$ for XRF 030723 (Smith et al. GCN 2338) closer to 0.01 day. None of the bursts from the sample in this paper have upper limits available. However, if the bursts with available upper limits are representative of the total GRB population, then it is possible that the bursts in our sample would have had similar upper limits, i.e., roughly 14-15th magnitude at ~ 500s. So there is a disagreement between the theoretical expectation and the observational upper limit.

There are several possible resolutions for this apparent discrepancy. The small optical flux could be due to much smaller magnetic field in the RS compared with the FS; for 990123 and 021211, however, ε_B in the RS was inferred to be larger than the FS, which perhaps might not be the common situation. Another possibility is that the deceleration time of GRB fireball is of order an hour instead of the burst duration of a few tens of seconds (assumed for the GRBs considered in this paper). Since the peak optical flux from RS is proportional to $\sim t_d^{-1}$ (see equations 25 & 26), the flux will be reduced by $\sim$3-5 magnitudes and therefore consistent with the observational upper limits of Kehoe et al. (2001). In this case the early lightcurve should be rising, and subsequently turn over to a steep decay at the deceleration time. The most likely explanation for a typically faint optical flux in our view is related to the low cooling frequency in the RS. We see from the table 2 that cases with a bright optical flash have cooling frequency below the optical band at deceleration, in which case the lightcurve should decline as $\sim t^{-3}$ and fade below the detection limit of 14-15 magnitude in a few hundred seconds.

The observational situation (whether bright reverse shock emission is typical or not) should become clearer when *Swift* is launched in September 2004.

5 DISCUSSION

We have explored the possibility that prompt γ-ray emission for a selected sample of 10 long duration GRBs might arise in the external shocks. These bursts had good multiwavelength afterglow data and temporal coverage which enabled Panaitescu and Kumar (2002) to determine their energy, jet opening angle, density of the surrounding medium, and microphysics parameters for the shock. We compared the observed peak flux and the peak frequency of the time averaged spectrum during the γ-ray burst with the theoretical extrapolation of the afterglow emission to the middle of the burst duration.

The motivation for considering external shocks for the generation of γ-ray emission for these 10 bursts is that most of these bursts are not highly variable, which is the primary reason for invoking internal shocks. Moreover, the efficiency for the production of γ-rays for these bursts is found to be

very high – in excess of 50% – which is difficult to understand in the internal shock models. In the particular case of GRB 990123 the γ-ray pulse width was of the same order as the time when the prompt optical emission from the reverse shock peaked i.e. the deceleration time. This means that the radius where γ-rays were generated was roughly the same as the deceleration radius, thereby suggesting a forward shock origin for gamma-rays. Moreover, the low energy spectral slope α ($f_\nu \propto \nu^\alpha$) for 990123 was 0.4, an observation that is difficult to understand in the internal shock models which have generally very low cooling frequency and therefore have $\alpha = -0.5$.

We find that it is not possible that the forward shock synchrotron afterglow emission, extrapolated back to prompt GRB duration, can explain the flux and peak frequency of nine of these ten bursts; only in the case of 970508, which was a single pulse FRED burst, does the extrapolation of the afterglow match up with the γ-ray emission property. Moreover, it turns out that even when we take ε_{Bf} (the energy fraction in magnetic field) and ISM density during the gamma-ray burst to be completely arbitrary, instead of the same as determined from afterglow modeling, we still cannot reconcile the gamma-ray observations with the theoretical calculations for seven of the ten bursts in our sample in the forward shock synchrotron emission model. The reason for this is that the forward shock is highly radiative at early times i.e., the cooling frequency during the gamma-ray burst is smaller than the synchrotron injection frequency, and therefore the flux at the peak of the νf_ν spectrum is independent of the density of the surrounding medium and ε_{Bf}, which happen to be the parameters with large uncertainty in afterglow modeling.

Two of the bursts in the sample, 980519 & 000418, can be understood as synchrotron emission in the forward shock provided that $\varepsilon_{Bf} \sim 1$ during the burst, a value that is larger by a factor$\sim 10^2$ than what we find during afterglow at ~ 1day; it is unclear if this is a physically sensible solution.

We have also considered inverse-Compton scattering of synchrotron emission from reverse or forward shock off of material in the forward and reverse shock regions, and find that it is not possible to explain the γ-ray emission, except possibly for 980703, with a reasonable set of parameters. In particular, the only solutions we found are when the circumburst medium is taken to have a wind like density profile with the density parameter about hundred times larger than the density of a typical Wolf-Rayet star wind and a few order of magnitude larger than the density determined from afterglow modeling.

Adding large density clumps to the external medium only increases the peak flux and frequency of νf_ν by a significant amount when the density of the clump and ejecta are similar when they collide to produce the γ-ray emission, in which case the early afterglow emission is extremely bright and hard to miss. Also, adding $e^\pm$ pairs to the ejecta decreases the inverse Compton flux, unless the electron distribution power law index is $\lesssim 2$, for any synchrotron-IC scattering scenario considered. Thus, neither of these two possibilities seem likely to explain the γ-ray emission properties of the bursts in our sample.

So, we are therefore forced to conclude that there must be another way to explain the GRB emission. The widely accepted internal shocks model might be the solution. How-

ever, considering the problem of efficiency, special cases of FREDs, and the problems for the internal shocks for 990123 discussed in §1, we feel it is prudent to explore other possible mechanisms such as the conversion of Poynting flux to radiation.

As for the reverse shock emission, we find that at least 50% of these ten bursts have bright prompt optical flashes, 9-11th mag, provided that the shock parameters – the energy fraction in electrons and magnetic field – in the reverse shock are the same or larger than the value in the forward shock. However, five of these bursts have cooling frequencies below the optical band and therefore the RS flux will decline very steeply with time (roughly as t^{-3}) and could easily go undetected after a few deceleration times. Those bursts with dimmer early emission generally have high cooling frequencies, and are assumed to exhibit the expected $1/t^2$ fall off. Although they are dim, they may still be detected.

If this sample of 10 bursts is representative of long duration GRBs then we expect very bright, rapidly fading ($\sim t^{-3}$), prompt optical flashes accompanying many γ-ray bursts. The RS emission is particularly bright just above the synchrotron self-absorption frequency of $\sim 10^{-1}$ eV where we expect the observed flux to be of order a Jansky, and declining rapidly with time since the cooling frequency is typically of the same order as the absorption frequency. It is also possible that the deceleration time is much longer than the GRB duration, which would reduce the predicted optical flux from the reverse shock. In this case we would expect to observe a dim, rising early optical afterglow lightcurve, turning over to a steep descent (t^{-2} or t^{-3}) after the deceleration time.

These issues will be resolved in the *Swift* era when we will have excellent early time coverage in the optical band for a few hours for many bursts. Future measurements of the early afterglow should enable us to determine if bright optical emission from the reverse shock is common, and thus determine the nature of the explosion, i.e. whether the explosion is baryonic, leptonic, or Poynting-flux dominated.

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